Chapter 3

Intraoperative Electroencephalography During Aortic Arch Surgery

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Abstract

Since its introduction, deep hypothermic circulatory arrest has been widely used for cerebral protection during aortic arch surgery. The use of electroencephalogram plays an important role in intraoperative neurophysiologic monitoring. Systemic cooling to the point of electrocerebral inactivity has been thought to ensure optimal neuroprotection from the ischemic injury during circulatory arrest. Therefore, electroencephalogram can guide surgeons to induce deep hypothermic circulatory arrest at an optimal timing. In the meantime, along with the advent of adjunctive cerebral perfusion techniques, there is a certain trend that circulatory arrest is induced at higher degrees than traditional deep hypothermic approach, called moderate hypothermic circulatory arrest. The role of electroencephalogram in this approach has not been well established yet, but some studies suggested the importance of intraoperative electroencephalogram in this approach as well. Electroencephalogram is also utilized in emerging operative techniques called hybrid arch repair. To conclude, intraoperative use of electroencephalogram can greatly contribute to cerebral protection in the field of aortic arch surgery, and surgeons should be familiar with its mechanism, indication, and interpretation.

Keywords: circulatory arrest, neurophysiological monitoring, aortic arch surgery, hypothermia

1. Introduction

Since its introduction, deep hypothermic circulatory arrest has been widely utilized for cerebral protection during aortic arch operations [1]. By inducing hypothermia to the brain and visceral organs, tissue oxygen and metabolic demands are reduced to the extent that the period of ischemia resulting from circulatory arrest can be well withstood [2–5]. Because the brain is particularly sensitive to transient periods of hypoxia, cerebral protection is essential during aortic arch operations. Despite the advancement of surgical techniques, perioperative neurological complications following aortic arch operations are still reported to be as high as 5–8% in the current era [6–8]. Therefore, optimal methods how to induce circulatory arrest safely are still debated.

It has been shown that body temperature measurement is not a sufficient indicator of brain temperature [9]. Stone and colleagues reported that when profound hypothermia is rapidly induced and reversed, temperature measurements made at standard monitoring sites may not reflect cerebral temperature. Although a number of modalities, such as near-infrared spectroscopy and transcranial cerebral oximetry, have been introduced to monitor the brain during aortic arch operations, no single technique has proven to be a perfect monitoring tool. A method of physiological monitoring, intraoperative electroencephalography (EEG), was introduced by Ganzel and colleagues in 1997 [10]. The viewpoint is that maximal cerebral protection is achieved at temperatures sufficient to induce electrocerebral inactivity on EEG, under the assumption that maximal suppression of cerebral metabolic activity is achieved at electrocerebral inactivity [2, 11]. Stecker and colleagues reported that the process of cooling to electrocerebral inactivity produced a uniform degree of cerebral protection, independent of the actual nasopharyngeal temperature [12]. Consequently, many institutions have introduced intraoperative EEG to allow for the identification of electrocerebral inactivity before initiating circulatory arrest [13–16], which leads to average minimum temperatures of less than 16°C [17, 18].

2. The intraoperative use of EEG during aortic arch operations

2.1. EEG changes during systemic cooling and rewarming

Keenan and colleagues provided a review about neurological monitoring during aortic arch surgery [19]. EEG is monitored through the process of systemic cooling to provide occurring assessment of electrocerebral activity as a marker for the extent of hypothermia-mediated metabolic suppression in the brain. EEG monitoring is generally provided by using gold disc electrodes attached to the scalp according to the International System of Electrode Placement. Baseline EEG needs to be obtained after anesthetic induction but before initiation of cardiopulmonary bypass and systemic cooling. Baseline EEG gives us the identification of baseline asymmetry or other abnormal findings in electrocerebral activity. With the initiation of systemic cooling, EEG amplitude begins to diminish. The sensitivity of EEG should be increased for better assessment of low-amplitude activity. Because electrocerebral activity is significantly influenced by anesthesia, anesthetic agents are usually discontinued during the systemic cooling in order to mitigate the confounding impact these drugs have on interpreting EEG.

Stecker and colleagues reported the pattern of EEG electrocerebral activity during aortic arch operations requiring deep hypothermic circulatory arrest [12, 18]. Between a nasopharyngeal temperature of 21.5 and 34.2°C, a majority of patients are found to have either lateralized, generalized, or bilateral independent periodic discharges, or transient and synchronous increases in EEG wave amplitude, against a background of continuous electrocerebral activity. Along with further systemic cooling, a gradual decrease in EEG continuity is found until the onset of a burst suppression pattern between 15.7 and 33.0°C. Finally, a progression to complete electrocerebral inactivity is found between 12.5 and 27.2°C (**Figure 1**).

During systemic rewarming, a reversed progression from electrocerebral inactivity back to normal amplitude continuous activity is found; however, the temperature points at which changes in EEG pattern tend to occur are different compared with the process of systemic

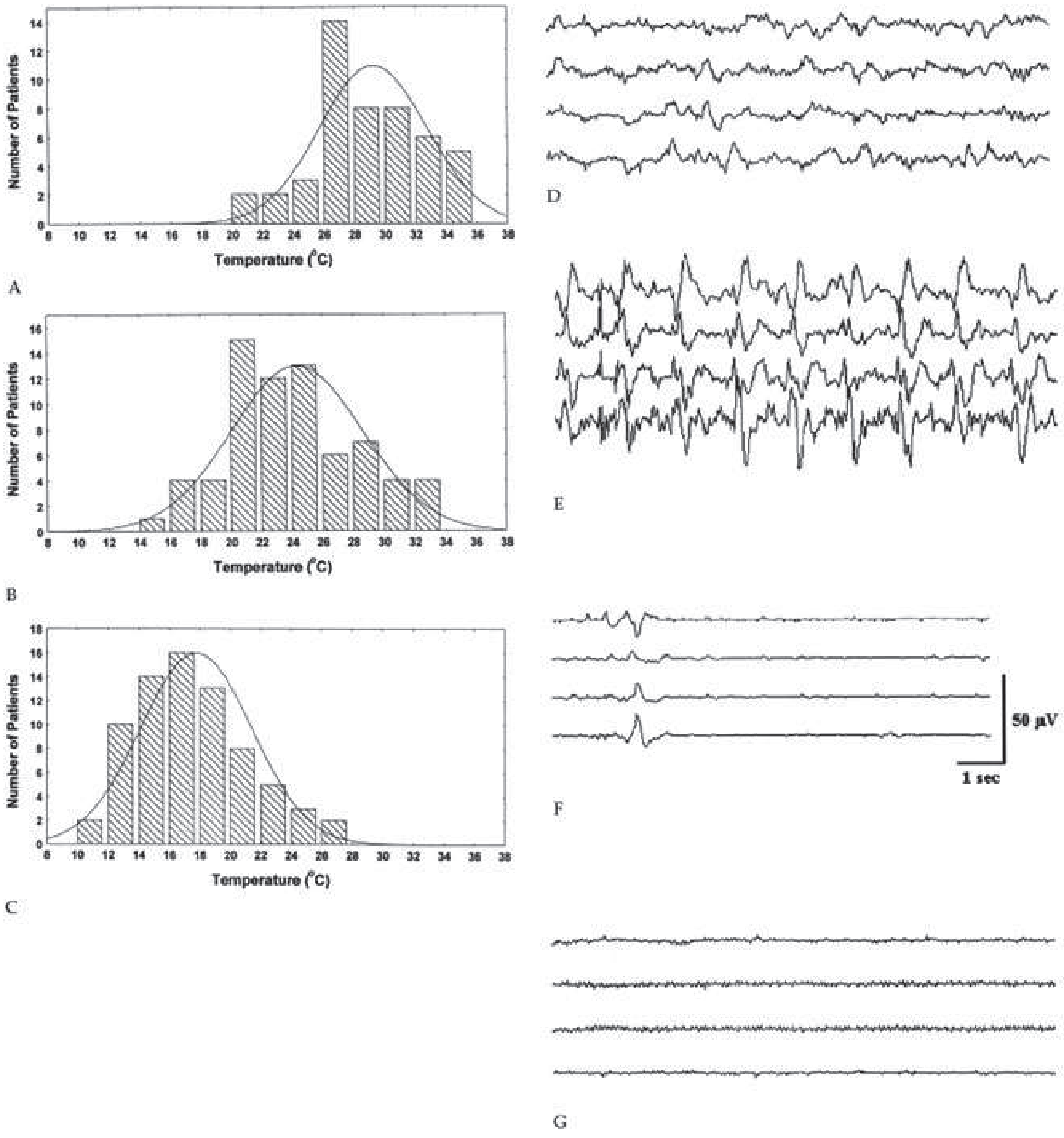

Figure 1. Distribution of nasopharyngeal temperatures at which various electroencephalogram landmarks occur: (A) appearance of periodic complexes, (B) appearance of burst suppression, and (C) electrocerebral inactivity. Examples of typical electroencephalogram patterns during systemic cooling are also shown: (D) precooling, (E) appearance of periodic complexes, (F) appearance of burst suppression, and (G) electrocerebral inactivity. Each of the electroencephalogram samples represent the following four channels from the left hemisphere (Fp1–F7, F7–T3, T3–T5, and T5–O1).

cooling. Therefore, while the changes of EEG pattern through the process of systemic cooling and rewarming are somewhat predictable, the temperature at which these EEG changes occur is significantly variable between patients. The required time for systemic cooling and rewarming is also variable and much depends of the patient and procedural factors [17, 18].

2.2. EEG findings during deep hypothermic circulatory arrest

The optimal degree of hypothermia before conducting circulatory arrest is still debated and remains a controversy in the field of aortic arch operations. Traditionally, the patient is cooled until electrocerebral inactivity is achieved prior to circulatory arrest, because electrocerebral inactivity is thought to be associated with minimal cerebral metabolic demand [2, 11]. Cooling to the point of electrocerebral inactivity has been thought to ensure optimal neuroprotection from the ischemic injury during circulatory arrest. Because the required time for achieving electrocerebral inactivity varies between patients and cannot be ensured by a specific temperature or a fixed duration (**Figure 2**), intraoperative EEG monitoring is crucial for surgeons to identify electrocerebral inactivity precisely before conducting circulatory arrest.

Previous reports regarding aortic arch operations have demonstrated increasingly good perioperative surgical outcomes, including low neurological complications and low mortality [13–16, 20–22]. In these reports, patients were cooled to the point of electrocerebral inactivity prior to initiation of circulatory arrest. This approach is generally called deep hypothermic circulatory arrest because deeper degrees of hypothermia and longer periods of systemic cooling are required to reach electrocerebral inactivity compared with alternative circulatory management strategies.

Murashita et al. reported the EEG findings during aortic arch operations performed under deep hypothermic circulatory arrest [22]. In their report, 135 out of 141 patients (95.7%) had normal recovery of EEG after termination of circulatory arrest and rewarming. Among them, 3 (2.2%) developed minor stroke. Overall 6 patients (4.3%) showed abnormal recovery of EEG, such as continuous suppression or asymmetric recovery. Of whom, 2 (33.3%) developed major stroke leading to 30-day mortality. Therefore, they concluded that patients who have abnormal EEG recovery are at high risk for postoperative major neurological complications.

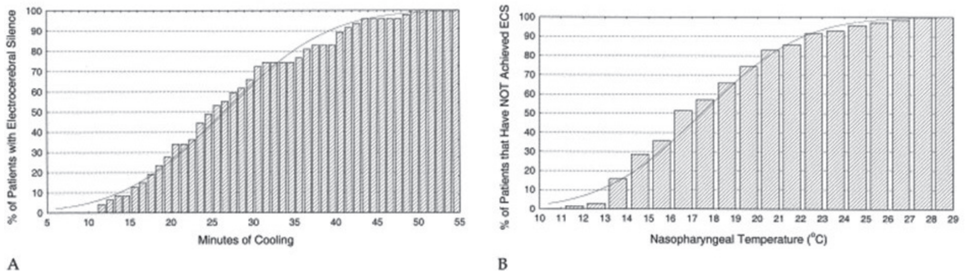

Figure 2. (A) The cumulative probability of electrocerebral silence on electroencephalogram as a function of cooling time. (B) The cumulative probability that electrocerebral silence is not achieved for temperatures above that indicated.

2.3. EEG findings during moderate hypothermic circulatory arrest

Although a deep hypothermic circulatory arrest is an established method in the field of aortic arch operations, there are concerns that the extremely low temperature can lead to adverse outcomes, such as hypothermia-related coagulopathy [23, 24], prolonged periods of cardiopulmonary bypass, or direct hypothermic neuronal injury [25–27]. In addition, the introduction of adjunctive cerebral perfusion techniques, such as retrograde and antegrade cerebral perfusion has allowed continued perfusion and cooling of the brain after systemic circulatory arrest. As a result, a number of institutions have been using a circulatory strategy of more moderate degrees of systemic hypothermia with adjunctive cerebral perfusion in aortic arch operations [28–33]. This circulatory strategy, generally called as moderate hypothermic circulatory arrest, has provided comparable or better surgical outcomes than traditional deep hypothermic circulatory arrest [34, 35]. There is a great deal of controversy regarding the superiority of moderate versus deep hypothermia. However, a trend of using higher degrees of hypothermic circulatory arrest than traditional deep hypothermia seems likely to continue.

Unlike deep hypothermic circulatory arrest, the role of intraoperative EEG monitoring in the setting of moderate hypothermic circulatory arrest has not well been established. In the setting of moderate hypothermic circulatory arrest, the timing of induction of circulatory arrest is usually determined based on the nasopharyngeal temperature between 20 and 28°C. There is a wide variety in the current literature regarding the definition of moderate hypothermia as well as the location of temperature measurement [36]. Most of the patients still demonstrate some form of electrocerebral activity in EEG at moderate temperatures, and the electrophysiological behavior of the brain around the time of circulatory arrest and the establishment of adjunctive cerebral perfusion techniques remains in the discovery phase.

Keenan and colleagues reported EEG findings during moderate hypothermic circulatory arrest during hemiarch replacement [37]. Their study included 71 patients who underwent hemiarch replacement with moderate hypothermic circulatory arrest. Nobody reached to electrocerebral inactivity at the time of circulatory arrest. Among 71 patients, 32 (45%) demonstrated an abrupt loss of electrocerebral activity immediately after circulatory arrest, indicative cerebral ischemia. However, the majority of them restored electrocerebral activity following establishment of unilateral antegrade cerebral perfusion (**Figure 3**). In the cases where unilateral selective antegrade cerebral perfusion (SACP) did not resolve the loss of electrocerebral activity, bilateral antegrade cerebral perfusion or further systemic cooling were required. **Figure 4** shows the case where unilateral selective antegrade cerebral perfusion did not restore the electrocerebral activity, but bilateral antegrade cerebral perfusion showed partial return of activity. In the remaining 39 patients (55%), electrocerebral activity was maintained in the brief period between circulatory arrest and selective antegrade cerebral perfusion and persisted after cerebral perfusion was established. There were no baseline characteristics between patients who had an abrupt loss of electrocerebral activity and those who did not. There were no postoperative stroke, transient ischemic attack, or permanent mental status change in both groups. They concluded that loss of electrocerebral activity following moderate hypothermic circulatory arrest can be restored by using adequate antegrade cerebral perfusion technique.

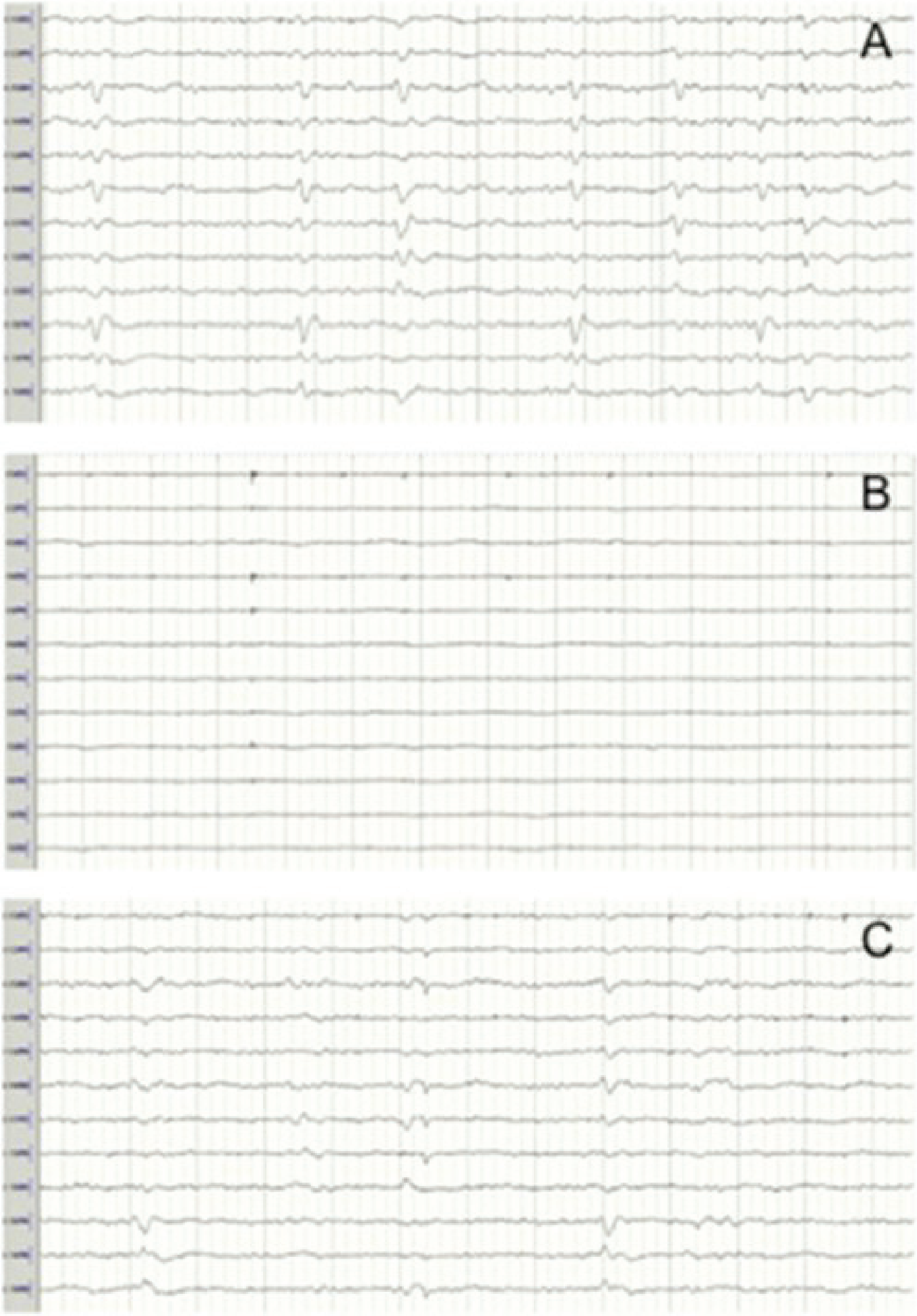

Figure 3. Restoration of electroencephalography (EEG) activity after circulatory arrest with the establishment of unilateral selective antegrade cerebral perfusion (SACP). (A) EEG before arrest shows burst suppression (nasopharyngeal temperature: 26.6°C). (B) EEG immediately after arrest demonstrates loss of electrocerebral activity. (C) EEG after unilateral SACP shows return of burst suppression pattern.

2.4. EEG use in emerging operative techniques

With the technical advancement of thoracic endovascular aortic repair, an innovative strategy that can avoid cardiopulmonary bypass and hypothermic circulatory arrest has emerged and become available for the surgical management of aortic arch pathology. That approach

Figure 4. Persistent loss of left-sided electrocerebral activity after establishment of selective antegrade cerebral perfusion (SACP). (A) Electroencephalogram (EEG) before arrest shows a continuous pattern with diffuse wave slowing (nasopharyngeal temperature: 28.1°C). (B) EEG after arrest demonstrates loss of electrocerebral activity. (C) EEG after unilateral SACP shows persistent loss of electrocerebral activity in the left-sided leads. (D) EEG after transition to bilateral SACP shows partial return of left-sided activity.

is known as a "hybrid" arch repair [38–42]. This technique usually consists of two distinct operations. The first operation is the open procedure for extra-anatomical bypasses of the great arch vessels. When there is concomitant ascending or proximal arch pathology, they need to be replaced. In that case, cardiopulmonary bypass and circulatory arrest will be necessary in the same way with conventional aortic arch operations. Therefore, intraoperative neurological monitoring using EEG needs to be taken into consideration. However, when ascending aorta and proximal arch replacement are not required, the first operation of hybrid arch repair does not require cardiopulmonary bypass or circulatory arrest. In that case, EEG with or without near-infrared spectroscopy is often used to detect brain ischemia, especially when innominate artery or left common carotid artery is bypassed [42]. The second operation consists of deployment of a stent-graft in which the proximal landing zone is within the ascending aorta or proximal aortic arch and the distal landing zone is within the descending aorta. Because the great arch vessels are already bypassed in the first operation, there is little or no concern for brain ischemia during the second operation. The use of EEG in the second operation is not as important as the first operation, and the attention is usually more paid to spinal cord ischemia in the second operation.

2.5. The effect of anesthetic agents on EEG

Anesthetic agents have a significant impact on the findings of EEG [43]; therefore, the intraoperative management of anesthetic agents is very important during aortic arch operations. Generally, intravenous anesthetic drugs, such as propofol, benzodiazepines, and barbiturates can have significant effects on EEG findings. Even at small doses, these drugs can induce burst suppression in EEG, and these changes can mislead physicians during the process of systemic cooling. Therefore, intravenous anesthetic drugs should usually be avoided, and their use should be discontinued by the time body temperature gets to 30–33°C.

Instead of intravenous anesthetic drugs, low doses of the halogenated inhalational agents including desflurane, isoflurane, and sevoflurane with opioids for analgesia generally consist of the basis of anesthesia during aortic arch operations. Although high dose of these agents can lead to increasing suppression in electrocerebral activity, low dose of these agents generally required for adequate surgical anesthesia is not associated with significant effects on EEG amplitude and frequency. Therefore, detection of shifts toward lower frequency and amplitude can be indicative of cerebral ischemia or other neurophysiological issues.

Besides anesthetic agents, non-pharmacological factors can also affect EEG findings. For example, reduction in systemic and local blood pressure induced by general anesthesia can affect EEG. Changes in partial pressure of oxygen and carbon dioxide induced by mechanical ventilation can change EEG findings as a result of either altered oxygen delivery or changes in cerebral blood flow. Therefore, it is crucial to take these effects into consideration when interpreting EEG findings.

3. Conclusions

Aortic arch operation is one of the most complex surgeries in the current era. The introduction of hypothermic circulatory arrest has provided a great safety in protection of organs, especially for brain. Neurophysiological monitoring using intraoperative EEG plays a critical role in this field to help surgeons direct circulatory management and give clues about conditions of brain ischemia. With the traditional deep hypothermic circulatory arrest approach, electrocerebral inactivity is usually achieved, and surgeons are ensured that circulatory arrest can be achieved safely. However, with the advent of adjunctive cerebral perfusion techniques, there is a certain trend that hypothermic circulatory arrest is achieved at higher degrees (moderate hypothermic circulatory arrest) than deep hypothermia where electrocerebral inactivity is not achieved, and the surgical outcomes with moderate hypothermia have been favorable. Moderate hypothermic technique can avoid the issues associated with deep hypothermia, such as coagulopathy, prolonged cardiopulmonary bypass, and direct neuronal injury. The electrophysiological findings in moderate hypothermic circulatory arrest have not been established and need to be studied further. It is highly likely that neurological monitoring using EEG in the aortic arch operations will continue to be viewed as a crucial modality to ensure optimal patient safety and as the field continues to develop with new circulatory management strategies and operative techniques.

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